A Review of Robotics Technologies for On-Orbit Services

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Space robotics has been considered one of the most promising approaches for on-orbit services (OOS) such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbit cleanup. Many enabling techniques have been developed recently and several technology demonstration missions have been completed. Several manned servicing missions were also successfully accomplished but unmanned real servicing missions have not been done yet. All of the accomplished unmanned technology demonstration missions were designed to service perfectly known and cooperative targets only. Servicing a non-cooperative satellite in orbit by a robotic system is still an untested mission facing many technical challenges. One of the largest challenges would be how to ensure the servicing spacecraft and the robot to safely and reliably dock with or capture the target satellite and stabilizing it for subsequent servicing, especially if the serviced target is unknown regarding its motion and kinematics/dynamics properties. Obviously, further research and development of the enabling technologies are needed. To facilitate such further research and development, this paper provides a literature review of the recently developed technologies related to the kinematics, dynamics, control and verification of space robotic systems for manned and unmanned on-orbit servicing missions.

I. Introduction

Statistic data reveals that in average about 100 satellites (from 78 to 130) were launched every year in the past decade. Most of them performed their missions without major problems. However, a small number of them experienced anomalies and even failures of various degrees of severity [1]. Although on-orbit satellite failures are rare, they are very costly, cumulatively accounting for losses of billions of dollars [2]. Additionally, every single satellite sent to the space, in a normal case after a few to fifteen years, would run out of fuel and thus, must be decommissioned although the satellite may still functional otherwise [3]. In such a case, it would be ideal to service such a satellite in orbit to resume its service or extend its mission. Using space manipulators for on-orbit services (OOS) has been recognized as a feasible solution. Such a possibility has been discussed in the aerospace research community and the space industry since the 1980s [4, 5], which has motivated much new technology development and several technology demonstration missions including both manned and unmanned missions [6].

ETS-VII of JAXA (Japanese Aerospace Exploration Agency) is considered the first robotic OOS demonstration mission, which has a 2 meter-long, 6-DOF (Degrees of Freedom) robotic arm mounted on one of the two unmanned spacecraft. The experimental system was launched in November 1997, with the intention of verifying technologies for autonomous rendezvous, docking, and robotic servicing in space [7]. The robotic experiments included a variety of tasks such as teleoperation from the ground with a large time-delay, robotic servicing task demonstrations such as ORU (Orbital Replacement Units) exchange, deployment of a space structure, dynamically coordinated control between the manipulator reaction and the satellite attitude, and capture and berthing of a target satellite. To avoid flying away due to a possible failed capture, the robotic capture task was performed while the two satellites were still physically tied using a latching mechanism [8].

The DARPA (Defense Advanced Research Projects Agency) developed an advanced technology demonstration mission called *Orbital Express*. The mission objectives were to demonstrate the ability to autonomously perform rendezvous and docking operations and on-orbit services such as refueling and ORU replacements [9]. The mission was successfully accomplished in 2007 [10]. Another DARPA on-orbital servicing program called SUMO (Spacecraft for the Universal Modification of Orbits) was initiated in 2005, aiming at combining detailed stereo photogrammetric imaging with robotic manipulators to autonomously grapple space objects for servicing [11]. The program later changed its name to FREND (Front-end Robotics Enabling Near-term Demonstration) [12]. It was to

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14. ABSTRACT
Space robotics has been considered one of the most promising approaches for on-orbit services (OOS) such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbit cleanup. Many enabling techniques have been developed recently and several technology demonstration missions have been completed. Several manned servicing missions were also successfully accomplished but unmanned real servicing missions have not been done yet. All of the accomplished unmanned technology demonstration missions were designed to service perfectly known and cooperative targets only. Servicing a non-cooperative satellite in orbit by a robotic system is still an untested mission facing many technical challenges. One of the largest challenges would be how to ensure the servicing spacecraft and the robot to safely and reliably dock with or capture the target satellite and stabilizing it for subsequent servicing, especially if the serviced target is unknown regarding its motion and kinematics/dynamics properties. Obviously, further research and development of the enabling technologies are needed. To facilitate such further research and development, this paper provides a literature review of the recently developed technologies related to the kinematics, dynamics, control and verification of space robotic systems for manned and unmanned on-orbit servicing missions.

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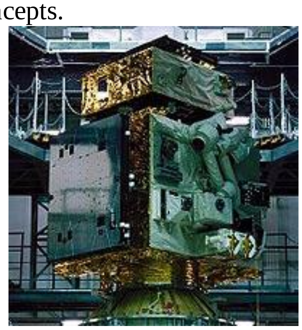
develop autonomous rendezvous and docking with satellites not pre-designed for servicing. This capability allows nearly any satellite to be repositioned on-orbit and provides a number of national benefits including better ground coverage in time of crisis, satellite life extension by eliminating the requirement imposed on fully functional satellites to expend their fuel to move to a safe disposal orbit, and disposal of derelict spacecraft which present navigation hazards to active satellites [13]. The US AFRL (Air Force Research Laboratory) in 2002 demonstrated some key elements of rendezvous and proximity operations with the eXperimental Satellite System 11 (XSS- 11) mission [14].

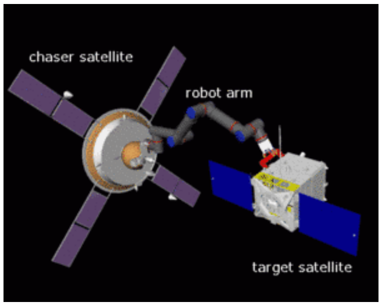
The National Aeronautics and Space Administration (NASA) sponsored the project DART (Demonstration for Autonomous Rendezvous Technology), which flew in 2005 [15]. The Objective was to demonstrate, the hardware and software necessary for autonomous rendezvous. The integration of an advanced video guidance sensor and autonomous rendezvous and proximity operations algorithms were intended. Unfortunately the proximity rendezvous operation was not fully accomplished due to excessive use of fuel. The spacecraft performed as planned for eight hours before a software glitch caused the spacecraft to fail.

Another recently planned OOS mission was called TECSAS (TEChnology SAtellites for Demostration and Verification of Space Systems) which was jointly developed by DLR (German Aerospace Center) of Germany, CSA (Canadian Space Agency) of Canada, and BSC (Babakin Space Center) of Russia. TECSAS consisted of a servicer satellite equipped with a robotic arm and a client microsatellite to be captured and serviced on orbit [16]. The mission comprises different phases in which a few features would be demonstrated, such as far rendezvous, close approach, flying-around inspection, formation flight, capture, stabilization and calibration of the coupled system, flight maneuvers with the coupled system, manipulation on the target satellite, active ground control via tele-presence, and passive ground control during autonomous operations. The multi-nation effort of this mission was discontinued due to priority shift of individual participating nations. Germany continued their development work and renamed the mission to DEOS (Deutsche Orbital Servicing Mission). The goal of the renamed mission is to find and evaluate procedures and techniques for rendezvous, capture and deorbiting of an uncontrollable satellite from its operational orbit [17]. The DEOS mission objectives are divided into a primary and secondary mission goals. The primary mission goal comprises capturing of a tumbling and non-cooperative satellite by a manipulator and controlled re-entry of the rigidly coupled satellites within a given re-entry corridor. The secondary mission goal comprises demonstration of the capturing procedure applying different methods with a free floating servicer in tele-presence operation and in autonomous operation, demonstration of the on-orbit servicing capabilities such as in-orbit replacement of a component and capturing of an attitude controlled satellite [18]. Fig. 1 shows the different on-orbit servicing concepts.

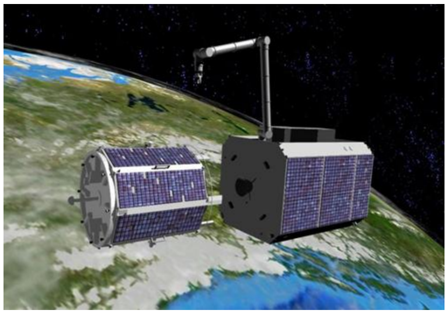


a) ETS-VII of JAXA [7]

b) Orbital Express of DARPA [9]



c) TECSAS of DLR/CSA/Babakin [16]



d) DEOS of DLR [17]

Fig. 1 Examples of the concepts of some on-orbit servicing missions

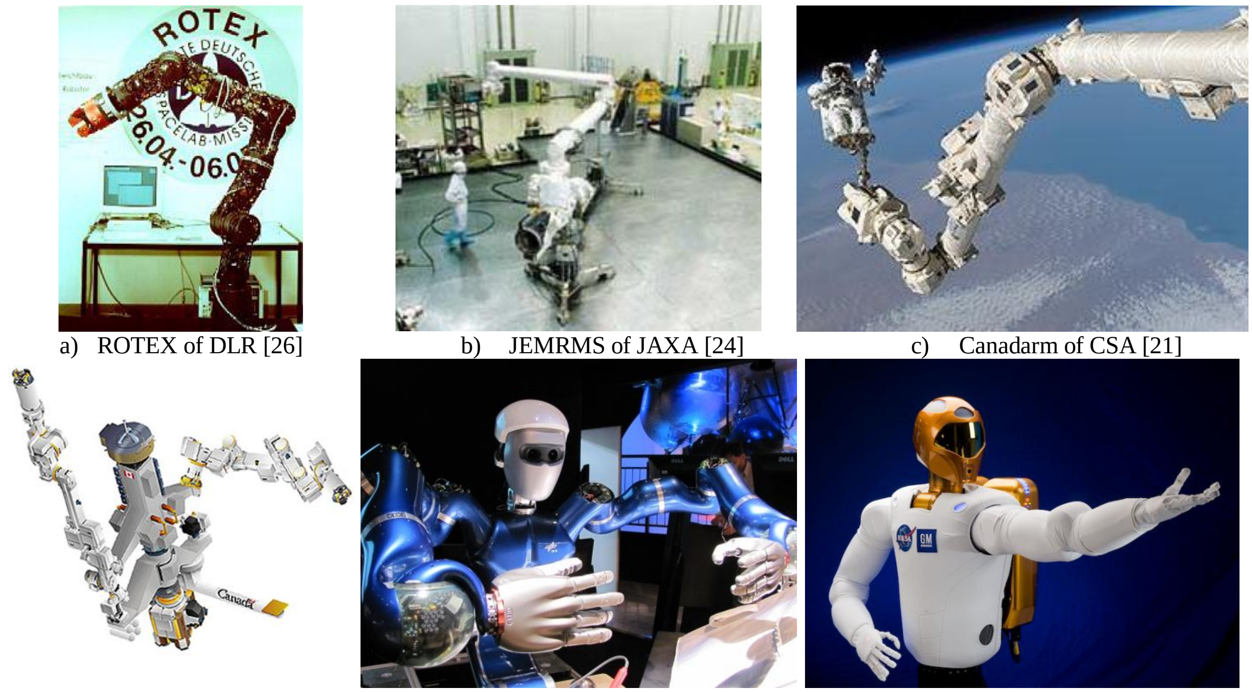
A couple of commercial OSS programs are underway right now. One is called CX-OLEV (ConeXpress Orbital Life Extension Vehicle) which is being developed by Orbital Recovery Limited (ORL) of UK to extend the lives of large geostationary satellites [19]. The other is being developed by Space Exploration Technologies (SpaceX), the first private company to launch a mission to the ISS (International Space Station). Their goal is to prove crew and cargo transportation services for the ISS, a job of the Space Shuttle in the past. The SpaceX vehicle has successfully accomplished its first docking with the ISS in May 2012, delivered about 1,200 lbs of water, food, and other supplies for the astronauts stationed in the ISS [20]. So far, the vehicles of both commercial programs have not been equipped with a robot arm.

A number of space manipulators have been developed and operated in space. The most well-known would be the Canada's Shuttle Remote Manipulator System (SRMS), also nicknamed Canadarm or Shuttle Arm, which was first launched in November 1981; the Space Station Remote Manipulator System (SSRMS), also nicknamed Canadarm2, which was launched in April 2001; and the Special Purpose Dexterous Manipulator (SPDM), nicknamed Dextre, which was launched in March 2008. The SRMS is a 6-DOF (6 degrees of freedom), 15-meter long robotic arm which was teleoperated by an astronaut inside the Space Shuttle. Over the past 30 years, the robotic arm has conducted numerous on-orbit service missions along with the Space Shuttle, such as deploying a satellite from the Shuttle's cargo bay to the space, maneuvering an astronaut for space walk, handing over a payload to another space robot SSRMS, etc. [21]. The SSRMS is a 7-DOF, 17-meter long robotic arm with a symmetric structure capable of walking on around the Space Station. The manipulator has a modular design for easy maintenance and force-moment sensors for advanced robotic control. It is has been used for the construction and services of the ISS and for the servicing of the Hubble telescope [22]. The SPDM has two arms, each of which has 7 DOFs and also equipped with force-moment sensors for advanced control. The robot is mainly used to perform maintenance of the Space Station and also to assist the astronauts for EVA tasks. There are another two space manipulators developed to serve the ISS. One is called ERA (European Robotic Arm) which was designed and made by ESA (European Space Agency) [23] and the other is called JERMS (Japanese Remote Manipulator System) which was developed by JAXA (Japan Aerospace Exploration Agency) [24]. ERA is a 11 meter long, 7 DOF manipulator with a reallocable base. JERMS consists of two 6 DOF arms, the 9.9 meters long one is intended to deploy large payloads and the small one is for more dexterous tasks [25].

DLR developed an experimental robot called ROTEX (RObot Technology EXperiment) to study and demonstrate robotics technologies in space. The system was flown onboard a space shuttle in April 1993 [26]. A variety of teleoperation modes were verified despite several seconds of delay, such as teleoperation on board, teleoperation from ground, and sensor-based offline programming. Key technologies for the success of the ROTEX were: the multisensory gripper, local sensory feedback control with intelligent sensory and the delay compensation 3D-stereographic-simulation [26]. DLR recently developed a servicing robot called ROKVISS (Robotics Component Verification on the ISS) [27]. They are also working in the development of a space humanoid robot named Space Justin, which is prototype capable of performing complex repair tasks in orbit. This humanoid has a head, torso, and arms, but no wheels or legs, because it will be mounted on a spacecraft or satellite. Justin will relieve future astronauts in dangerous missions in space and will be used to repair or refuel satellites that need to be serviced. The eventual goal is to have Justin operate autonomously, but in the short term, it will be teleoperated from the ground [28]. A few space robots are shown in Fig. 2.

NASA advanced in the development of a more dexterous robot called Robonaut 1 (R1) with the objective of assisting astronauts with EVA tasks. R1 has demonstrated its ability to work with existing EVA tools and interfaces in high-fidelity ground-based test facilities [29]. Further, NASA and General Motors (GM) developed a second generation of R1, the Robonaut 2 or R2 for flight testing on ISS. This is a state-of-the-art, dexterous, anthropomorphic robotic torso that has significant technical improvements over its predecessor making it a far more valuable tool for astronauts. Upgrades include: increased force sensing, greater range of motion, higher bandwidth, and improved dexterity [30]. R2 has been launched to ISS in February 2011, becoming the first humanoid robot in space.

A space robotic system for an OOS mission typically consists of three major parts, namely, the base spacecraft or servicing satellite, a robot manipulator based on the servicing satellite, and the satellite to be served. The servicing satellite and the manipulator comprise the servicing system, as depicted in Fig. 3. The capturing process includes a series of operations. Most of the researchers tend to separate them into four phases [31]. The first is the observing and planning phase for acquiring motion information of the target satellite and planning when and where the robot will grasp the target satellite. The second phase is to control the robot to move toward the planned grasping location to make the robot ready for the capturing of the target. The third phase is the capture (physical interception) phase in which the manipulator physically captures the target satellite. The fourth phase is the post-capture phase in which captured target satellite is stabilized along with the servicing system.



a) ROTEX of DLR [26] b) JEMRMS of JAXA [24] c) Canadarm of CSA [21]

d) Dextre of CSA [21] e) Space Justin of DLR [28] f) Robonaut 2 of NASA-GM [30]

Fig. 2 Examples of space robots for extra vehicular activities.

The paper is organized as follows: the basic approaches for the kinematics and dynamics of space manipulators are presented in Section II. It is followed with a description of the schemes for accomplishing an approaching maneuver in Section III. In section IV, path planning and control techniques for approaching a target satellite are discussed. Section V outlines the methods for capturing the target satellite with the less reaction on the base and the proposed stabilization approaches. Section VI analyses the flexibility problem presented in the space manipulators. In section VII the existing test facilities used for ground-based verification are described. The paper is concluded in Section VIII.

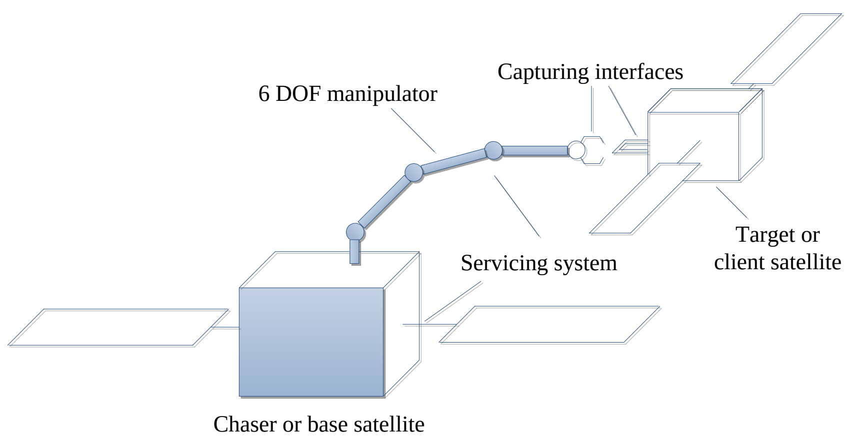


Figure 3. Components of a Space Manipulator for On-orbit Servicing.

II. Kinematics and Dynamics of Space Manipulators

The main difference between space manipulators from ground-based ones is that the base of a space manipulator is not usually fixed to the ground. It is instead flying or freely floating (including rotating) in the orbital environment. Special attention should be paid to the dynamic coupling between a manipulator and its base during the modeling of the robot. Movements of the manipulator disturb the attitude of the satellite carrying it, complicating the kinematics and dynamics analysis of the space manipulator [32-34]. The workspace is reduced as well [35, 36].

As regards the base spacecraft, three types of operation are considered. The first type corresponds to the free-flying case, where the base is actively controlled and hence, the entire servicing system is capable of being transferred and orientated arbitrarily in space. The utilization of such a system may be limited because the manipulator motion can both saturate the reaction jet system and consume large amount of fuel [37]. In the second type, the base attitude is controlled by using reaction wheels, leaving the spacecraft only in free translation. These two categories are split because in some cases only the control of the attitude change is enough to reach the target position and to avoid loss of communication with ground stations and disorientation of solar panels. The third is the free-floating case, where the attitude control of the base is inactive and thus, the base is completely free to translate and rotate in reaction to the manipulator motion. Some of the authors merge the first two categories (fully actuated and partially actuated) into the free-flying case.

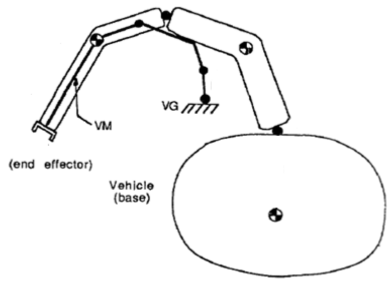
In general the forward kinematics problem for a space manipulator becomes a dynamic problem with the property that the robot's end-effector position at the end of a maneuver is not only a function of the final joint angles, but also depending on the time history of the joint angles and the inertial properties of the system. The equations of the forward kinematics problem were derived and one feasible solution, among infinite numbers of possible solutions, was obtained for the complicated inverse kinematics problem in [35]. Also, the authors analyzed the workspace of a free-floating space manipulator and claimed that it was a perfect sphere. Further, the workspace was also load dependent, shrinking as the load increasing.

Umetani and Yoshida [38] developed an inverse kinematics solution by defining the *Generalized Jacobian Matrix* (GJM). They further showed that the GJM is be very close to the conventional Jacobian matrix of the same manipulator as if it was fixed to the ground when the mass of the manipulator is much smaller than the mass of the base spacecraft. It was shown in [39] that the rank of the GJM is deficient at some configurations in the manipulator's joint space, which causes the manipulator unable to move its end-effector in some direction of inertial space. These singularity configurations cannot be determined solely by the kinematics of the system, instead, they also depend on the system's inertia properties. Hence, they are called *dynamic singularities*. The authors also showed that the end-effector's linear and angular velocities in inertial space can be expressed solely as a function of the manipulator joint angles and rates, and that they do not depend upon the uncontrolled linear and angular velocities of the base spacecraft.

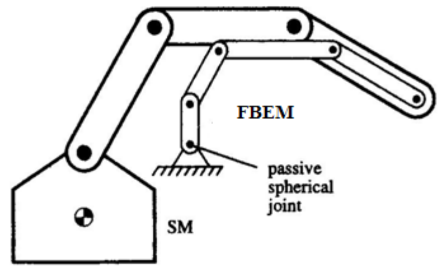
Vafa and Dubowsky introduced the concept of *Virtual Manipulator* (VM) in [33] to simplify the kinematics and dynamics of a space manipulator. The VM is a massless kinematic chain whose base is fixed in the inertial space at a point called the virtual ground (VG) and whose tip is at an arbitrary point on the real manipulator tip. The VG is located at the center of mass of the manipulator-spacecraft system. This point doesn't move in the inertial space when there are no external forces. Once the VM is constructed, it moves with the real manipulator. The endpoint of the VM is always coincident with the end point of the real manipulator. These properties enable both kinematics and dynamics of a space manipulator system to be modeled in the same way as these of the corresponding VM which is a ground robot because its base is always fixed in the inertial frame.

Note that a VM is an idealized massless kinematic chain and thus, it can only be simulated in a computer and cannot be physically built. This means that the concept of VM cannot be used as an experimental test bed for space manipulators. In [40] the *Dynamically Equivalent Manipulator* (DEM) is proposed. The DEM goes beyond the VM concept because it represents the space manipulator both kinematically and dynamically and thus, it can be physically built for experimental study of the dynamic behavior of a space manipulator. The DEM is a fixed-base manipulator whose first joint is a passive spherical joint and whose kinematics and dynamics models are identical to those of the corresponding space manipulator system. The first joint is fixed in the same point where the VG of the VM is located. The lengths of the links are also the same as those of the VM. The dynamics of the DEM maps identically the dynamics of the space manipulator under the action of a control law. This equivalence is valid not only for the free-floating case where the base attitude is uncontrolled but also for the case where the base attitude is actively controlled. The DEM was employed to test the control methods which were originally developed for fixed-base manipulators but would be used for space manipulators. The DEM was used to develop an adaptive controller [41]. The concepts of VM and DEM for a simple space manipulator are shown in Fig. 4.

A solution of the inverse kinematics problem for space manipulators was presented using optimization criteria rather than applying conventional schemes based on pseudo-inverse matrix methods [42]. The use of multiple arms for capturing a satellite has also been studied. An explicit dynamics model of a multiple manipulator system was presented based on direct path kinematics approach [43]. Derivation of the equations of motion resulted in an explicit formulation of the system's mass matrix and the generalized nonlinear inertia forces. The obtained explicit dynamics model of a multiple-arm manipulator can be implemented either numerically or symbolically. To handle the dynamic singularities, in [44] a method called *Singularity Separation Plus Damped Reciprocal* (SSPDR), was proposed. The approach separates the singularity parameters from the inverse Jacobian matrix, replaces their reciprocals using the damped reciprocals, and combines that information with the measured angular velocity of the base. Then, the dynamic singularity problem is transformed into a kinematic singularity problem which can be handled by many existing techniques.



a) A three body space manipulator and its VM [33].



b) A four space manipulator and its DEM with its first joint being spherical [40]

Figure 4. Virtual manipulator (VM) and dynamically equivalent manipulator (DEM)

A critical portion of the dynamics modeling for the OOS applications is contact dynamics (including low-speed impact dynamics). Contact dynamics is one of the most difficult areas in multibody dynamics and is still an active research subject. The main modeling difficulties arisen from the complicated geometries of the contact interfaces such as the ones shown in Fig. 5. A survey of general contact dynamics modeling techniques can be found in [45]. An early application of contact dynamics in space robots was reported in [46]. Ma et al [47, 48] developed a generic contact dynamics modeling and simulation system to support the development and operations of the ISS robotic systems SSRMS and SPDM. They further developed a model reduction technique to improve the efficiency of high-fidelity but usually very time-consuming contact dynamics simulations [49]. Nenchev and Yoshida [50] also addressed the contact dynamics modeling and control issues for space manipulators. Ma et al [51], developed control strategy for achieving high fidelity contact dynamics simulation of a new, robotics-based, hardware-in-the-loop (HIL) rendezvous and docking simulation. They used the EPOS facility as simulation platform to validate their methodology. Abiko et al [52] introduced a contact dynamics simulation for capturing a floating target by a long reach space manipulator with a snare wire type end-effector. The authors used this kind of end-effector because current space manipulators such as the SSRMS are equipped with a latching end-effector with three snare wires inside. An experimental evaluation of the contact/impact dynamics between a space robot and tumbling object was introduced by Uyama et al [53]. In this work the authors modeled the contact force as a spring-dashpot model. Thus, they used the Hertz model to obtain the contact force. Sawada et al [54] focused on the contact dynamics of the manipulator's end-effector and the grapple fixture of a target satellite. To validate the method they set-up a hybrid simulation using a numerical model and 6 DOF robot with a 6-axis force-torque sensor. The authors also employed a three-wired EE mechanism.

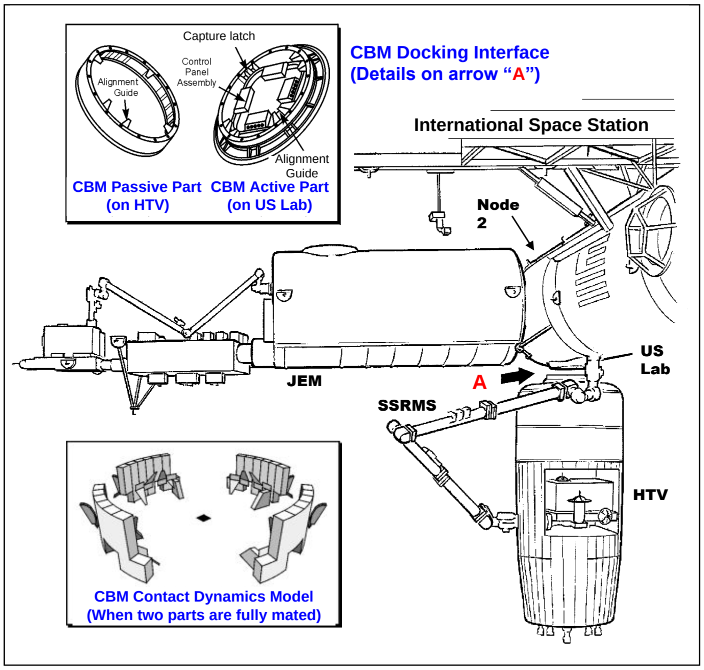


Figure 5. Contact interfaces for robotic berthing the H-II Transfer Vehicle (HTV) to the ISS

III. Observation and Planning Phase

The objectives of the observation and planning phase are to acquire the 6-DOF motion information of the target including the position, attitude, linear and angular velocities of the target body, determine when and where to grasp the target, and plan the motion trajectory for a final approaching and capturing. Since a malfunctional satellite or orbit object may be in tumbling motion and/or have unknown kinematics/dynamics properties. Therefore, it becomes essential to predict its motion pattern and identify its kinematics/dynamics parameters. Another necessary task for OOS consists of guiding the space manipulator to perform proximity rendezvous to the target satellite. The term proximity means the servicing spacecraft has completed its orbit transferring and phasing and has been in a very short distance to the target satellite [55].

A. Target Motion Prediction and Parameter Identification

Nagamatsu et al. proposed a 12th order extended Kalman filter method to estimate the position and attitude of a target satellite [56]. To verify the validity and applicability of the method, experiments were performed to capture a free-flying object by using a 3-D hardware simulator with a 5-DOF manipulator. Huang et al. [57] used the estimation scheme developed in [56] to develop an algorithm for tracking trajectory planning. The authors assumed that the target is nearly axis-symmetric and the target's size, shape and mass are all known. Besides, the handling location is determined by human inspection. Therefore, it is also assumed that the target is equipped with visual markers, signal reflector, and GPS device for simplification. Thienel et al. [58] took advantage of the fact that the Hubble Space Telescope (HST) is equipped with vision-based sensors to develop a method for estimating the rates of the HST. The method was used in the estimation part of a tracking control scheme in [59]. Assuming that an object is not acted upon by any external force and moment, the motion of the target satellite was predicted in [60]. Litcher and Dubowsky, using 3-D vision sensors, proposed an architecture for estimation of dynamic state, geometric shape, and model parameters of an object in orbit, with potential application to a satellite capturing [61]. It is very desirable to predict the motion of a target as soon as possible. Therefore, in [62] the motion and the parameters were estimated from range data as may be measured by stereo vision or a laser range sensor, which allows faster prediction. The possibility to perform inertial parameters identification of the base spacecraft and the payload directly in orbit using accelerometers data is shown in [63]. Xu et al. also proposed an autonomous path planning method for target capturing in [64, 65]. The target features are extracted based on the visually measured information via the hand-eye camera and the target pose (position and orientation) and velocities are estimated using a Kalman filter scheme. Disturbance on the base due to manipulator's motion is also estimated and reduced. The authors validated the method using both computer simulations and experiments. Along the same line, from noisy measurements of vision system, a Kalman filter was used to estimate the motion state and some dynamics parameters for the capture of a tumbling satellite in [66]. A 3D-image generated by a PMD (photonic mixer device) camera was used for determination of the relative distance and orientation, as well as the motion identification of the satellite [67]. On the other hand, McCourt and Silva used a model predictive control in the space manipulator to deal with the problem of the unknown dynamics of a target satellite [68].

The inertia parameters of a target satellite may not be the only unknowns. Due to fuel consumption, hardware reconfiguration, payload deployment, or capturing of a flyer, the inertia properties of the servicing satellite may also change. Therefore, dynamics parameters identification methods have been proposed to handle this problem [69]. Morotsu et al. [70] proposed two parameter identification methods. One is based on the linear an angular momentum conservation law and the other on Newton-Euler equations of Motion. Ma et al. proposed an inertia identification method which uses an onboard robotic arm to excite the angular velocity changes of the base spacecraft and then using measured angular velocity changes to identify the unknown inertia parameters of the base spacecraft [71]. Since the method uses a robotic arm which is powered by solar energy, it does not require the use of fuel. Further, since the method is derived from the momentum equation of the system, it requires the measurement of velocities only and does not need any information of the acceleration and energy-dissipating internal forces.

B. Proximity Rendezvous for Autonomous Capturing

Most of the actual rendezvous technology deals with controlled targets. However, a space robot for OOS may demand the proximity or close-range rendezvous with a non-cooperative target satellite. A two-phase navigation solution for rendezvous with a tumbling satellite in 2D space was studied by Fitz-Coy and Liu [72]. The target vehicle is uncontrolled but has assumed constant linear and angular velocities. It was shown that this kind of maneuvers requires two phases. In the first phase, the LOS (line-of-sight) rotation is driven to zero while aligning the capturing mechanisms of the two vehicles. The second phase requires a transverse navigation constant of 2. In [73] a method for matching angular velocities between the servicer and target by changing the target's moments of inertia is presented. Matsumoto et al. [74] proposed a passive fly-by approach and an optimal trajectory for close-range rendezvous with a rotating satellite, considering issues such as collision avoidance between the manipulator and the target satellite. Ma et al. [75] designed an optimal trajectory for a spacecraft to approach a tumbling satellite by minimizing time and fuel. They obtained the required thrust force profiles that would guide the chasing spacecraft to approach the tumbling satellite such that the two vehicles would eventually have no relative rotation and thus, a subsequent capture operation can be safely performed with a normal docking or capture mechanism. Xin and Pan [76-77] developed an optimal control of spacecraft approaching a tumbling target. They minimized the flexible motion induced by large angular maneuvers by employing the $\theta - D$ nonlinear optimal control technique. Once the position and the attitude were measured based on stereo vision, autonomous rendezvous and robotic capturing of a non-cooperative target was proposed by Xu et al. [78]. 3D simulation results were performed to verify the algorithm. Using the information provided by their prediction algorithm [66], the authors in [79]. An optimal approaching motion was obtained in [80] which assumed unknown target’s inertial property.

IV. Final Approaching Phase

In order to perform on-orbit servicing, the servicing satellite, which is assumed carrying a manipulator, has to first approach in a desired trajectory to the target satellite. Here, approach implies the approaching motion of a manipulator or manipulators to the target satellite.

A. Free-floating Case

In the absence of external forces, the system’s linear and angular momenta should be conserved. Although both of them are represented by velocities, the linear momentum is exhibited by the motion of the center of mass of the whole system and can therefore be integrated into equations of positions instead of velocities. This implies that the linear momentum equations are Integratable. On the other hand, the angular momentum equations cannot be represented by their integrated form, which means that they are nonholonomic [81]. Some researchers have used these nonholonomic and redundant characteristics to develop interesting solutions for robot path planning [82].

A.1 Non-holonomic Path Planning

Inspired by an astronaut's motion allowing him/her to reorient his/her body by just moving limbs, Vafa and Dubowsky [36] proposed a special cyclic motion trajectory of a manipulator's joints to change the base spacecraft's orientation. They called the method *Self-Correcting Motions*. In the method a nominal trajectory is selected for the end-effector and base orientations. Then, the selected joint motions are executed assuming that the base remains stationary. If at any point the base orientation deviates from its desired path by more than a specific amount, then a selected series of small cyclic motions is added to the joint motions to correct the vehicle orientation. The same authors introduced a technique called *Disturbance Map* (DM) [83], which can aid in selecting paths that reduces the disturbances of the spacecraft by identifying the direction of the joint movements which results in minimum or maximum disturbances. The method ignores the effort of the attitude control system and assumes that the system has zero initial angular momentum. DM can be constructed by dividing the space manipulator joint space into a grid of points. At every point the directions of minimum and maximum spacecraft movements are plotted. Later, Dubowsky and Torres [84] presented an improved version of the DM called *Enhanced Disturbance Map* (EDM) and showed how it can be effectively used to plan the manipulator motion to reduce the disturbances to the base spacecraft.

The EDM was used in manipulators with more than two degrees of freedom while the original DM was used only for 2-link planar case. The same authors showed in [85] that the EDM can be used with the objective of minimizing the fuel usage for attitude control. Another extension of the DM concept to the case of planar polar manipulators was presented in [86].

Papadopoulos [87] proposed a path planning technique in Cartesian space that not only reduces the disturbance but also avoids the dynamical singularities. The author found that a workspace point may or may not induce a dynamic singularity, depending on the joint space path taken to reach it. To solve this ambiguity, he defined the *Path Dependent Workspace* (PDW) to contain all workspace locations that may induce a dynamic singularity. If the PDW is subtracted from the reachable workspace, the *Path Independent Workspace* (PIW) is obtained. All the points in the PIW are guaranteed not to have dynamic singularities. Pandey and Agrawal [88] proposed a method called *Mode Summation* for planning a Cartesian path of a free-floating system with prismatic joints. Their method avoids inversion of the Jacobian matrix and it also results in a singularity-free path for the end-effector. However, the requirement for the desired final attitude is not taken into account. Lampariello and Deutrich [89] applied a similar method, but to a system with rotational joints only. To overcome the dynamic singularity problem in Cartesian space path planning, Xu et al. [90] used the direct kinematic equations. In their method the joint trajectories were parameterized by polynomial or sinusoidal functions first. Then, the joint functions were normalized and the system of equations about the parameters is established by integrating the differential kinematics equations. Finally, the parameters were solved by iterative Newtonian method. The drawback of the method is that the convergence time may be long because of the numerical iterations. Furthermore, there exist different paths to reach the desired pose because of the nonholonomic nature of the free-floating system.

Fernandes et al. [91] showed that the falling cat problem is equivalent to the nonholonomic motion problem of a free-floating space robot and they used this analogy to develop a near-optimal motion planning method. The authors applied the method directly to a space manipulator platform in [92], using a 3-DOF Puma robot as the manipulator attached to a space platform. One drawback of the approach is that, it needs symbolic manipulation software to obtain the Jacobian matrices which are required by the algorithm.

The path planning problem of a free-floating target with a manipulator having angular momentum, was addressed by Yamada in [93, 94]. To find a closed-loop path, the authors proposed a variational optimization approach in joint space for trajectory planning. In that way, the required change of the satellite orientation can be obtained using joint control only. Suzuki and Nakamura [95] demonstrated that a free-floating space robot with 6 DOFs cannot follow an arbitrary desired trajectory in the 9-D generalized coordinate space (3 coordinates for the base spacecraft and 6 for the manipulator) with only the joint controls. Then, they proposed a method to approximate the desired 9-D path by introducing a perturbation around the path. They call the approximated trajectory *Spiral Motion*. With the objective of reducing the disturbances on the base, Yoshida et al. proposed the *Zero Reaction Maneuver* (ZRM) in [96]. The ZRM is obtained by making zero angular velocity of the base in the angular momentum equation. The existence of the ZRM is limited to 6-DOF manipulators. Most of the above-mentioned methods are time consuming. A computationally inexpensive method developed for terrestrial mobile manipulator systems was extended for potential use in space robotics [97] but it has not been validated yet.

The *Bi-directional approach* requires that the joints stop at the switching point and the Self-Correcting method is based on small cyclical motions. Such techniques yield non-smooth trajectories. Papadopoulos et al [98] proposed a smooth planning methodology in joint space for planar free-floating space manipulators that allows endpoint Cartesian location control and a simultaneous control of the base attitude. In the method, smooth and continuous functions such as polynomials are employed. Further work showed that the final configuration accessibility is improved drastically when high order polynomials were used for the joint angle solution. The planning problem was reduced to solving a set of nonlinear equations, representing the integral of motion. Based on the same idea, the authors of [99] developed a numerical path planning approach for the general case of an *n*-DOF manipulator. Taking into account of the dynamics of large space manipulators, Belousov et al. [100] proposed two 'two-stage' iterative algorithms, which can generate collision-free robot motion paths.

Recently, Franch et al [101] have employed flatness theory to plan trajectories for free-floating systems. Their method requires the selection of robot parameters so that the system is made controllable and linearizable by prolongations. Agrawal et al. extended this method to a three-link spatial space robot in [102]. Using genetic algorithms, a non-holonomic path planning was introduced by Xu et al. [103]. The method's advantages are: the motion of the manipulator and the disturbance to the base are practically constrained; the planned motion path is smooth; and the convergence of the algorithm is not affected by the singularities. A non-holonomic path planning method was proposed based on a particle swarm optimization [104]. The method was applied to the target berthing and base re-orientation after the capture of a target.

A.2 Non-holonomic Control

To compensate for the base motions, different control algorithms have been presented. Resolved Motion Rate Control for a space manipulator using the GJM was proposed by Umetani and Yoshida [105]. This method has also been applied to redundant systems [106] and multiple-arm control [107]. Nenchev et al. [108, 109] developed a specific joint decomposition technique, called *Fixed-Attitude-Restricted* (FAR) motion, which allows a manipulator arm to move without inducing any reaction moments to the base spacecraft. Along with the solution of a conventional end-effector trajectory tracking, a solution of base motion control was also obtained. The use of a dual-arm manipulator for minimizing disturbances to the base spacecraft is suggested in [110, 111]. In the method one of the arms is controlled to compensate for the disturbance caused by the other arm.

Another motion control was developed based on the general three-dimensional equations of motion. Instead of performing a single inverse kinematics calculation at the beginning of a movement, multiple inverse kinematics updates based on an optimal algorithm are performed [112]. Control strategies using an underactuated space manipulator to reduce the load and power-usage, have also been proposed [113]. This study revealed that it is possible to make all the manipulator's joints converge to the desired values by controlling only the actuated joints. Efficient algorithms for computing the GJM and the resolved acceleration control for multi-arm space robots were presented in [114]. Based on the second method of Liapunov, Xu et al. [115] proposed a robust control to overcome the difficulty in controlling the internal dynamics subject to parameter uncertainties. The Coupling Factor as a measurement of the degrees of dynamic coupling was defined in [116-117]. This measurement can be considered as a performance index in the planning of the robot motion control. During operation, small amounts of angular momentum tend to accumulate. Therefore, the ability to work on orbit under this condition is studied in [118-121]. Some of the efforts being done in the nonholomic path planning and control were discussed in [122-123].

Major advances in the kinematics and dynamics modeling and path planning as well as control of free floating space robots in the early nineties were reported in [124]. Those seminal works have laid a good theoretical foundation for most of the newer developments in the past decade.

B. Free-flying Case

The self-correction motion method proposed in [36] assumes small cyclic motion to neglect the nonlinearities of order greater than two and it requires many cycles to make even a small change in the vehicle orientation. To solve that problem, Nakamura and Mukherjee [125] proposed a path planning scheme that deals with the total nonlinearity of the satellite/manipulator system. The method is based on a Lyapunov function to control both the base orientation and the manipulator joints by actuating the manipulator's joints only. The scheme is called *Bi-Directional Approach*. Two desired paths were planned, one starting from the initial configuration and going forward and the other starting from the initial configuration and going backward. A drawback of this technique is that it is affected by singularities. To increase the mobility and perform larger tip displacement, free-flying space robotic systems in which the associated manipulator is mounted on a thruster-equipped spacecraft, were proposed [126,127]. This kind of robotic systems requires a coordinated controller of the base spacecraft and the manipulator. Xu et al. [128], proposed an adaptive control with an attitude control on the base. The method avoids the use of joint acceleration measurements, inversion of inertial matrix, and high gain feedback. Based on augmenting the control requirements to include the location and attitude of a system spacecraft, Papadopoulos and Dubowsky [129] presented a coordinated control of both the base spacecraft and the manipulator. They used a transpose-Jacobian type controller. Oda [130-131], also addressed the problem of coordinated control, where the robot control system estimates the angular momentum that the robotic arm produces and then the satellite attitude control system compensates the arm's reaction.

To achieve the goal of capturing and manipulating a space object, using multiple manipulators is an interesting approach. Dynamics modeling of multiple-arm systems and motion control of the end-effectors coordinated with the base spacecraft to chase a moving object was proposed in [132-133]. The authors improved their control algorithm by using the *Modified Transpose Jacobian* (MTJ), which allowed storing data from the previous time step control command [134]. Based on a nonlinear inversion technique, De Rivals-Mazères et al. [135] described the position and orientation of the base and the joint angles of a flexible manipulator by deriving a control law that controls the output variables. Taking into account the kinematic and dynamic constraints, an optimal motion for a free flying system is formulated in [136]. The solutions were found for local and global motions. For the latter, the unnecessary spacecraft actuation was shown to be efficiently avoided. However, the final attained spacecraft attitude is known before hand, and it is obtained only after optimal solution is implemented.

V. Capturing and Post-Capturing Phases

The capturing phase involves physical interception and thus is highly risky. The goal would be to capture the moving target without destabilizing the attitude of the base spacecraft. Once the target is successfully captured, the combined system must be stabilized as soon as possible.

A. Free-Floating Case

An early effort of studying the effect of physical contact between a space manipulator and a tumbling object was reported in [137]. Their system aimed at simulating the catching and handling of a free-flying target with the manipulator installed on a light structure such as a space satellite, only relative 6-DOF motion between the target and the robot is simulated. While the manipulator is in contact with the target, the momentum is derived by integrating the force measured by force/torque sensors. The effect of impacts upon a flexible-link free-floating space robot was discussed by Cyril et al [138]. The method also aid in the determination of the initial conditions for post-impact simulations. Since it is difficult to sense the impact force precisely because impact is very high speed phenomenon and force sensor signal is very noisy, Yoshida et al [139] modeled the Collision dynamics, using the Extended Generalized Tensor (Ex-GIT) without sensing the impact force. Ex-GIT is an extension of the conventional GIT for ground-based chains. They formulated the collision problem focusing on the velocity relationship just before and after the impact considering the momentum conservation law. The authors also proposed the concepts of Impulse Ellipsoid and Impulse Index to conveniently express impulse characteristics. In addition, in order to account for the joint behavior with resistance during the impact, the theory was improved by introducing the concept of Virtual Rotor Inertia [140]. However, the analysis mainly focused on the moments just before and after the collision. Yoshikawa and Yamada [141] followed this concept and provided mathematical proof in the frequency domain and the method was experimentally verified in [142]. Wee and Walker [46] studied the dynamics of contact between space robots and developed an algorithm to achieve both trajectory tracking and impulse minimization. Their study reveals that the impulse at contact could be minimized by the optimization of a scalar cost function based on the gradient projection technique. Impact experiments for estimating the impact effect are reported in [143],[144], the experimental platform consists of a rigid manipulator supported by a flexible deployable structure. In [145], Yoshida and Nenchev introduced the concept of Reaction-Null Space (RNS), which corresponds to the null-space of the coupling inertia matrix. Using the RNS, they found out proper manipulator configurations, to achieve a safe capture and minimize the impact. The authors extended the study to investigate the joint reaction and the base reaction due to the impulsive force [146]. They used the RNS and the FAR technique to analyze the pre-impact phase and develop a post-impact control law keeping the base reaction in a minimum value. One drawback of this method is that since it is based in the angular momentum conservation, after the impact, the momentum is exchanged between the base and the manipulator to finally use additional base actuators to stop the system. However, this approach allows having the momentum with the lowest velocity in the manipulator and effectively stops the angular momentum of the base in a relatively short period of time.

Cyril et al [147] studied the dynamics associated with the capture of a spinning satellite. Nevertheless, it is assumed that at the time of capture there is zero relative velocity between the payload and the end-effector of the manipulator. Cyril and Jaar [148] analyzed the behavior of a space manipulator capturing a flexible payload during the impact and the post-capture phase. Papadopoulos and Paraskevas [149] proposed a methodology based on the well known from basic dynamics Percussion Point of Bodies to minimize the forces instead of the momentum transmitted to the base of the manipulator when grasping an object. The authors proposed some guidelines for the best configuration of mechanism at time of impact. Huang et al [150], also found that the configuration of the space manipulator at the contact moment is an important factor to consider in order to reduce the impact effect. Then, in [151], an optimal approach trajectory planning method for minimizing the impact is proposed, and in order to minimize or avoid the impact effect, in [152] the authors used a genetic algorithm to search optimal configuration of a space manipulator at the capturing instant.

During the impact phase, the interaction with the environment should be considered. Hybrid position/force control has been a basic strategy adopted. However, control mode switching is required at many points during the task [153]. To solve that problem, in [154] impedance control is proposed for controlling the dynamic interaction of manipulators with the environment. Contact motion between a space manipulator and a non-cooperative satellite is formulated in [155-156]. The authors used impedance matching to give a criteria if the contact is maintained with the target or if the target is pushed away. Experiments are carried out using two robot manipulators as a motion simulator of the servicer and target. Most of previous works model the contact dynamics only as an impulse force acting on the tip of the manipulator. Nevertheless, in reality, the contact model is more complicated. A contact model should be included for a more realistic study. In [157, 158] a Simulink©-based satellite docking simulator with the capability of simulating contact behavior such as: impact, bouncing, sliding, rolling spinning, sticking and jamming, is presented. A robotics based simulator for verifying microgravity contact dynamics is developed in [159]. Flores-Abad and Ma proposed a methodology to reduce the impact effect during the capturing process [160]. A contact dynamics analysis for space robotics applications is presented in [161]. The contact force direction is estimated based on the known geometries and motion states of the end-effector and the grapple fixture on the target. Using the estimated contact force and the observed target motion, an optimal capturing time and location are determined such that the resulting physical contact for capturing will cause minimal attitude impact to the base spacecraft.

B. Free-Flying Case

To control the system after grasping the object, an adaptive approach was employed considering the flexibility of the transported object [162]. With the objective of reducing the disturbances on the base spacecraft during contact with the target, control of multi-arm cooperating manipulator is proposed in [163, 164]. Multiple impedance control strategy has been developed for several cooperating manipulators [165] and also applied to a space robot with multiple arms [165,166] both, the manipulator's end-effector and the capturing object are controlled to behave like the designated impedance in reaction to any disturbing external force on the object. Hence, an accordant motion of the manipulator and the payload is achieved. As shown in [167], force tracking can also be achieved using impedance control. Methods in [162-167] assumed that the input force to the base from the robots can be controlled perfectly. However, the thrusters cannot provide accurate position control because the output forces of the thrusters are constant, and only the total impulse may be controlled by varying the thrusters durations [168]. Therefore, Nakanishi and Yoshida [169-170] presented a control method that does not require precision in the base control. The end-effector of the manipulator is controlled like a mass-damper-spring system fixed at a point in space regardless of the reactive motion of the base.

Another possible solution for the capturing problem is from the viewpoint of angular momentum. Grasping a target satellite without considering its momentum imposes difficulties for the post-impact control, and most likely the capturing operation will fail. One method utilizes a device with controllable momentum wheels (“space leech”), which has to be attached to the target and absorb the angular momentum [171]. In [172] the idea of rotational motion-damper is proposed. Using contact/push based method, the angular momentum from the target is partially transferred to the servicing satellite. However, this could results in separation from the target after each contact and therefore the usage of gas-jet thrusters for linear motion is unavoidable. This method might be useful if the amount of angular momentum in the target is very large and direct capture is impossible. A similar method using Impulsive Control is proposed by Yoshikawa et al. [173]. An experimental verification of the strategy is reported in [174]. Nakamura et al [175] utilized a "tethered retrieve" which is guided to the target through the tension force in the tether and thrusters positioned on the retriever. During the post-impact phase the angular momentum of the target is “absorbed” in attitude devices positioned on the retriever. In [176] the service satellite makes a fly around maneuver in such a way that the capturing operation can be conducted with small relative motion between the two systems.

The authors proposed a free-motion path method which enables to completely ignore the nonlinearity effect in the dynamics by taking advantage of the conservative quantities of the system.

A capture strategy to minimize the base attitude disturbance from the viewpoint of angular momentum management was discussed in [177]. The technique is called *Bias Momentum*. Moreover, a method to control the transfer of the angular momentum from the target to the robot base by controlling the arm motion is proposed in [178]. However, the two latter problems solved above occur simultaneously in the capture operation. Hence, a control method which can realize the consecutive contact so that the target is not pushed away and the suppression of the undesirable base rotation is required. Such a strategy is discussed in [179]. In order to guarantee conservation of contact, impedance control is utilized and the Distributed Momentum Control (DMC) is used for zero base rotation. Yoshida et al [180] proposed a possible control sequence for the successful completion of a capturing operation. The authors used the bias momentum approach during the approaching phase, impedance control during the impact phase and DMC during the pos-impact phase. Inaba et al. [181] presented some design requirements when using a space robot to capture a satellite. Special attention was paid in the image processing for the visual servoing.

In order to reduce and even eliminate the base reactions during a contact, control-moment reaction gyroscopes (CMGs) were proposed as actuators for space manipulators [182]. It was shown that the power consumption was the same as that of a robotic system driven by conventional joint motors. Usually impedance control is preferred for contact control [154]. A time delay on impedance control may occur in reality, which can cause the impulse of the contact to be very large. In [183], experiments and numerical simulations were carried out to verify the effect of the time delay of impedance control. Reaction devices, like gas-jet thrusters or reaction wheels, have limitations on available output torques. It is not possible for the thrusters to compensate the vast angular momentum to stabilize the base in a short time duration after the impact. In [184] a time-optimal manipulator control strategy was addressed considering constraints in the output torque of a system using reaction wheels. The method assumes that the path trajectory is given in advance. It was shown that desired output torques of reaction wheels were explicitly related to the reaction torques induced by the manipulator motion. The proposed control strategy was verified by numerical simulation with a space manipulator model, which has a 7 DOFs and three reaction wheels. References [185, 186] address an optimal control of a space manipulator in the post-capture phase to bring the tumbling non-cooperative satellite to rest in minimum time while ensuring that the magnitude of the interaction torque between the manipulator and the target remains below a prescribed threshold.

Once a manipulator has captured a target satellite, the manipulator and the target become a single system with combined mass properties and dynamics characteristics. In order for the controller to handle these changes, an adaptation law may be designed. Satoko and Hirzinger [187] proposed an adaptive controller for this purpose. They focused on the uncertainty of kinematic mapping, which included the dynamic parameters of the system. To achieve the desired input torques, a velocity-based-closed-loop servo control is used. Liang and Ma [188] introduced an adaptive control approach, which can be used to assist the control of a servicing satellite to rendezvous and dock with or capture a tumbling satellite. A Lyapunov-based tracking law and an adaptation law were proposed to guarantee the success of the nonlinear control.

VI. Flexibility and Vibration Suppression

Due to launch mass limitations, space manipulators are intended to be light-weighted, thus, they are not ideal rigid bodies, but are more likely flexible mechanical structures, which can increase the complexity during their operations. Therefore, it is also important to study the effect of such structural flexibility [48, 189]. Torres and Dubowsky presented the Coupling Map to plan motions of elastically constrained space manipulator systems for lower vibration to its supporting elastic base [190]. A study on the dynamics and control of large flexible space structures was presented in [191], where the authors validated their method using a LQG/LTR and H_∞ controllers. Another piece of work dealing with links flexibility was reported in [192] where they approximated the bending due to the flexibility using the static bending curve of Shimoya. With the objective of suppressing the vibrations due to the links flexibility in the Japanese space manipulator (JEMRMS), Abiko and Yoshida [193] introduced and adaptive controller. Ma and Wang [194] presented a model reduction for impact-contact dynamics simulations of flexible manipulators. They first linearized the contact force model and then applied the traditional modal analysis and reduction techniques to reduce the order of the resulting dynamics equations for more stable and efficient simulation process. In [195] Sabatini et al modeled the vibrations generated due to the flexibility in the links as well as in the joints of the manipulator and designed and studied active damping strategies and devices that could be used to reduce the structural vibrations.

VII. Ground Verification: Materials and Methods

Just as any other space systems, a space manipulator and its associated control systems must pass all the verification tests on the ground before it can be launched to the space. For the dynamic test of control functions and performance, the test facility should be able to simulate microgravity conditions and allow 6-DOF motions of the robotic system. The most commonly used technology for such a purpose is an air-bearing based floating test facility. Such a system usually includes one or two mobile platforms floating on a flat floor through air bearing pads. It allows the simulation of two vehicles approaching and docking in 2D or 3-DOF space which includes one rotational and two translational DOFs. More DOFs of maneuvering may be added by suspending the tested object with a multi-DOF mechanism but more massive hardware has to be added and the dynamics properties of the test system would also be altered accordingly. Such a method has been applied for testing the control algorithms of Japanese free-floating systems [196], and during the free-flying experiments at Stanford University [197]. All the major space companies and some research groups in academia own this kind of facilities such as the ones described in [198-201].

Another technology of simulating microgravity is to use a water pool to achieve neutral buoyancy, so that the submerged body has an equal tendency to float as it would in space. This method has the advantages that an experiment can be carried out in 6-DOF space and without time duration constraints. Massachusetts Institute of Technology has performed many tests of a teleoperated manipualtor using NASA's neutral buoyancy lab [202]. University of Maryland also owns such a facility and it has been used to explore the arm-base interaction for a free-flying robot called *Ranger* [203,204]. Researchers of the University of Padova are developing a free-flying robot prototype with one extended arm suitable for under-water conditions [204]. The neutral buoyancy technology suffers from the drag force induced by the water which does not exist in the space and it is also very expensive to operate. Moreover, all the tested hardware units must be made water proof or sealed, which means that the real space hardware cannot be tested as is.

An airplane flying in a parabolic trajectory can also be used to achieve microgravity condition. In [205] a 4-DOF robotic arm was tested in a parabolic flight, under 0.02g for a 20-second time period generated by an MU-300 aircraft. Menon et al [206] carried out two flights of 30 parabolas each. Parabolic flight tests were performed to evaluate an attitude controller for a tethered robot in [207]. This microgravity simulation technology suffers several obvious drawbacks such as: too short time duration (10~30 seconds) of microgravity condition, very limited work space due to the small volume inside the aircraft, and very non-smooth or jittering working environment due to the aircraft motion [208]. Microgravity environment can also be generated by free-falling experiments. Iwata et al. [209] achieved 3×10^{-3} g for 10 seconds from a distance of 710 m, and Watanabe et al [210] obtained 1×10^{-5} g for 10 seconds by a free falling experiment from a vertical distance of 490 m. Both experiments were performed at the Japan Microgravity Center (JAMIC). The time interval of 0g condition using this method is even less than the parabolic flight and, if it is not performed very carefully, the robot can be easily damaged.

The gravity force may be compensated by a suspension system or balancing mechanism for zero or reduced gravity testing of a space manipulator [211]. Such a system generates compensating forces of the same amplitude but in the opposite direction as the gravity force of the tested robot. Sato et al. [212] developed an experiment to test a free-floating space manipulators using such a method. Brown and Dolan [213] suspended a robot with a cable from an electromechanical system that passively generates mechanical counterbalance forces. White and Xu [214] also developed an active gravity compensation system. Their testbed utilizes lightweight cables passing through several pulleys before terminating in the counterweight that has the same effective mass as the simulated robot. Menon et al. [200] suspended the base of the robot employing an inextensible cable fixed in the vertical projection of its center of mass, while the arm links are hung by springs. The main drawback of this technology is obviously a static balancing of the gravity force and thus the system cannot preserve the true microgravity dynamics of a space manipulator as it experienced in the space. Further, all the suspension cables, as long as they are not perfectly vertical during a test, apply extra tensions to the tested robot in non-vertical directions which can significantly alter the multi-DOF dynamic behavior of the tested space robot. This problem may be solved by the method of using a multi-DOF statically balanced mechanism as the one proposed by Ma et al. [215]. The mechanism employs springs to achieve multi-DOF gravity balancing at each configuration within the workspace of the mechanism.

The combination of hardware test and computer simulation is an attractive new approach for verification of space robots performing complicated contact tasks. Since the technology involves both hardware test and software simulation, it is called hardware-in-the-loop (HIL) simulation. With this technology, a high-bandwidth hardware robotic system acts according to the commands sent by software that simulates the dynamics of the space manipulator working in the space environment [216]. Such a system helps not only to reproduce the approaching phase but also the capturing/docking phase. The first hybrid simulator reported was developed by Shimoshi et al.

[137]. They combined numerical simulation and servo mechanisms. The system consisted of a facility robot, a 5-DOF translational target, and software simulating the dynamics of the space robot. Agrawal et al. [217] proposed two possible laboratory setups to achieve the relative motion of a free-floating robot with respect to the space target. In both cases the target is mounted on the end-effector of the facility robot. CSA developed a sophisticated HIL simulation system called STVF (SPDM Task Verification Facility), shown in Fig. 6, to simulate the dynamic behavior of the space robot SPDM performing maintenance on the ISS [218]. The simulation facility has been accepted as the formal verification tool for the acceptance of the SPDM. The space robot has been successfully launched to the ISS and is currently performing its regular services there. Figure 7 shows some of these facilities.

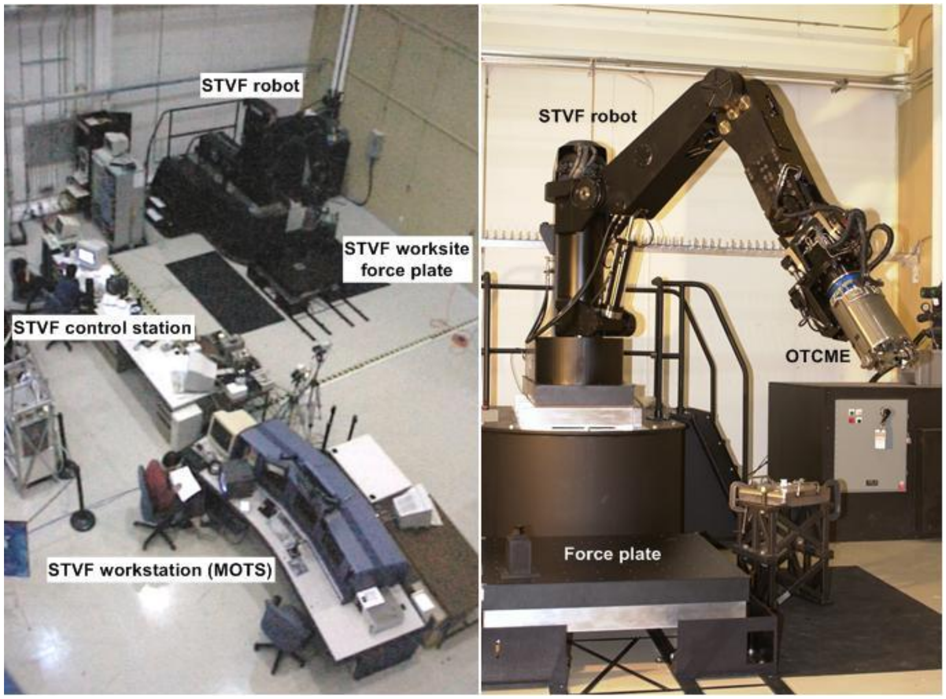
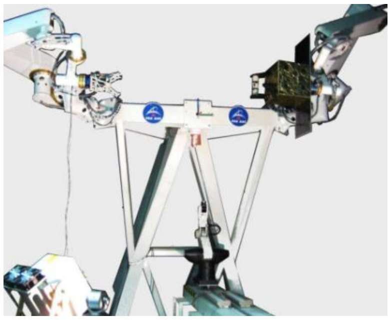
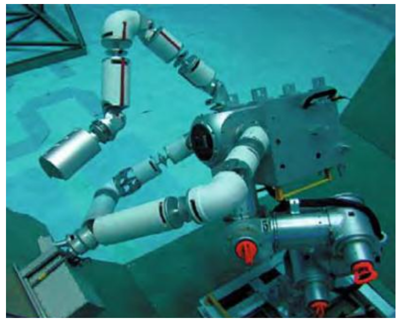


Fig. 6 SPDM Task Verification Facility (STVF) [216]

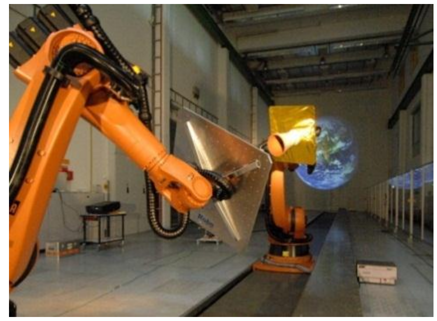
Dubowsky et al [219] implemented a dual-robot HIL simulation system which consists of a PUMA manipulator as robot A and a Stewart platform as robot B. The emulation was done using admittance control, so that the Stewart platform moved according to the desired admittance model. DLR recently developed a dual-robot HIL simulation system called *European Proximity Operations Simulator* (EPOS) [220]. In the system, two industrial KUKA robots are employed, one of which behaves as a servicing satellite and the other as a target satellite. The system is capable of simulating proximity rendezvous and docking of two spacecraft. The facility is currently being used to support the development of the DEOS and other OOS missions [221]. Takahashi et al. [222] used a 14-DOF dual-arm robot and a 9-DOF motion table (including a 6-DOF parallel robot) to verify orbital operations. It is also an HIL simulation system. Some other experimental test facilities were also developed to support space robotics and OOS technology developments [223-225]. HIL simulation is powerful for testing complex space systems for complicated robotic tasks but it also suffer some drawbacks. First, since the system driven by simulation, the mathematical model of the spacecraft or space robot has to be accurate and the simulation must be performed in real time. Second, the hardware part of the system must have sufficient bandwidth and proper impedance, so that the active hardware system produce high-fidelity behavior close enough to the real space robot. Finally, the system has to be able to deal with the inevitable time delay from a hardware contact to the corresponding simulation-driven reaction at the tip of the facility robot (not the immediate and passive reaction of the facility robot). Some researchers have proposed techniques to handle the HIL time delay problem [226, 227].



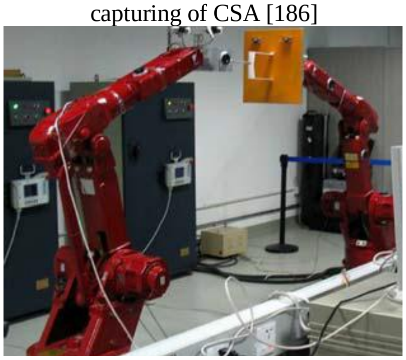
Experimental facility for autonmous capturing of CSA [186]



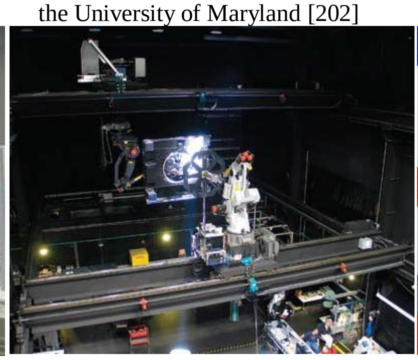
Neutral buoyancy Research Facility of the University of Maryland [202]



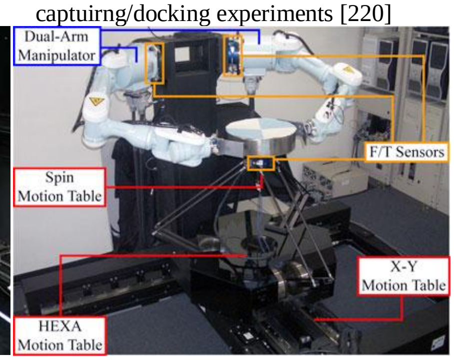
EPOS system of DLR for captuirng/docking experiments [220]



Ground experimental system of HIT [223]



Facility for autonomous docking experiments of DARPA/NRL [225]



Hybrid simulator for orbital operations experiments of the Tohuku University [227]

Figure 7. Facilities for testing a space robotic system to capture a free-flying satellite or object in space

VIII. Conclusion

It has been shown that on-orbit services (OOS) such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbit cleanup are of increasing interest to the space industry because of the high economical potential and also the strategic benefits. As a result, many enabling techniques have been developed in the past two decades. These development works have been reviewed with an emphasis on the key areas of kinematics, dynamics, trajectory planning, control, and ground-based experiments. In addition, several technology demonstration missions have been successfully accomplished. A review of these accomplished missions revealed that all of them were designed to service perfectly known and cooperative targets only. Servicing a non-cooperative satellite or space object in orbit such as a tumbling satellite or a piece of space debris by a space robot is still an untested mission facing many technical challenges. There are several challenges involved in the use of robotics technology for on-orbit servicing, such as: the parameters estimation and motion prediction of target object, the attitude disturbance of the base satellite generated as a reaction to the manipulators motion, the difficulties to guarantee a safe and reliable capture and docking operation and the posterior stabilization of the system, the time delays, and the difficulties to simulate a microgravity 6 DOF environment, among others. Therefore, further research and development of the enabling technologies are desperately needed. It is hoped that this literature review will help the further research.

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